

Long-lived heavy neutrinos from neutrinophilic charged Higgs at the HL-LHC

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Based on: [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)

with Nobuchika Okada and Ravindra Kumar Verma

Revisiting Type-I 2HDM

- ▶ $\mathbb{Z}_2$ symmetry evades the FCNC problem, leading to four Yukawa types: **Type-I, II, X and Y**.
- ▶ $-\mathcal{L}_Y^I = \bar{Q}_L Y_u \tilde{H}_1 u_R + \bar{Q}_L Y_d H_1 d_R + \bar{L}_L Y_l H_1 l_R + \text{h.c.}$
- ▶ Small H_1 – H_2 mixing and $v_2 \ll v_1$: $h \in H_1$ and BSM Higgses $H^\pm, A, H \in H_2$.
- ▶ The mostly H_2 BSM Higgses have suppressed Yukawa couplings to SM fermions.

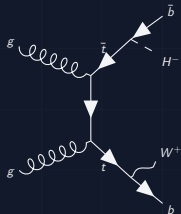
BSM Higgses: $H, A, H^\pm$



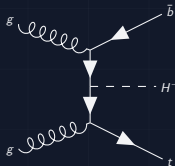
SM Fermiophobic



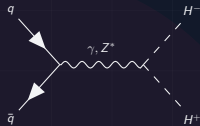
Suppressed QCD production cross section



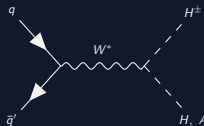
Light $H^\pm$ QCD production



Heavy $H^\pm$ QCD production



EW $H^\pm$ pair production



EW $H^\pm$ production in association with H, A

QCD vs EW production of $H^\pm$

EW production remains sizable and can exceed the QCD induced production

Neutrinophilic Higgs doublet

- ▶ Neutrino mass matrix in canonical seesaw:

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

m_D : Dirac mass matrix

m_N : Majorana mass matrix

$m_D \ll m_N$: Seesaw hierarchy

- ▶ The BSM (neutrinophilic) Higgs doublet H_2 couples to the SM lepton doublets and gauge singlet right-handed neutrinos (N_R).

$$-\mathcal{L}_y \supset y_D^{ij} \bar{L}_{Li} H_2 N_{Rj} + \text{h.c.} \quad \text{and} \quad m_D = \frac{y_D}{\sqrt{2}} v_2$$

The small VEV $v_2 (\ll v_{EW})$ of the neutrinophilic Higgs doublet naturally generates small Dirac neutrino masses, even for sizable Dirac Yukawa couplings

- ▶ Diagonalization of the neutrino mass matrix gives:

$$m_\nu = -m_D m_N^{-1} m_D^T$$

$$R = m_D m_N^{-1}$$

m_ν : Light neutrino matrix

R : Light-heavy neutrino mixing matrix

$$D_\nu = U^T m_\nu U = \text{diag}(m_1, m_2, m_3); \quad m_N = \text{diag}(m_{N_1}, m_{N_2}, m_{N_3}) \quad \text{and} \quad U : \text{PMNS matrix}$$

- ▶ Flavor-mass eigenstate relation:

$$\nu_\alpha = U_{\alpha i} \nu_i + R_{\alpha i} N_i \quad \alpha : \text{flavor index}, \quad i : \text{mass index}$$

$$[A] \quad -\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu \bar{\ell}_\alpha \gamma^\mu P_L (U_{\alpha j} \nu_j + R_{\alpha j} N_j) + \text{h.c.}$$

$$[B] \quad -\mathcal{L}_{NC} = \frac{g}{2c_W} Z_\mu [\bar{\nu}_i \gamma^\mu P_L \nu_i + \bar{N}_i \gamma^\mu P_L (R^\dagger R)_{ij} N_j + \bar{\nu}_i \gamma^\mu P_L (U^\dagger R)_{ij} N_j + \text{h.c.}]$$

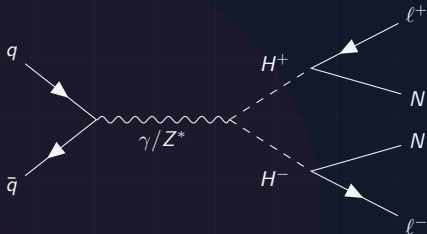
SM gauge boson induced production of heavy neutrinos is mixing suppressed

- ▶ Neutrinophilic $H^\pm$ decay to heavy neutrinos and SM charged lepton:

$$\Gamma(H^+ \rightarrow \ell_\alpha^+ N_i) = \frac{|m_{D_{\alpha i}}|^2}{8\pi v_2^2} m_{H^\pm} \left(1 - \frac{m_{N_i}^2}{m_{H^\pm}^2}\right)^2$$

and assuming small H_1 – H_2 mixing, $H^\pm$ decay to heavy neutrinos is 100% if kinematically allowed.

- ▶ $\sigma_{\text{prod}} = \sigma(pp \rightarrow H^+ H^-) \times BR(H^\pm \rightarrow \ell^\pm N)^2$



Neutrinophilic $H^\pm$ pair production via EW process remains sizable.

This provides an alternative production channel for gauge-singlet heavy neutrinos through $H^\pm \rightarrow \ell^\pm N$, without suppression from light–heavy neutrino mixing

Long-lived heavy neutrinos

$$\blacktriangleright \Gamma(N_i \rightarrow \ell_\alpha W) = \frac{|R_{\alpha i}|^2}{8\pi} \frac{(m_{N_i}^2 - m_W^2)^2 (m_{N_i}^2 + 2m_W^2)}{m_{N_i}^3 v^2} \text{ and } \Gamma(N_i \rightarrow \nu_\alpha Z) = \frac{|R_{\alpha i}|^2}{16\pi} \frac{(m_{N_i}^2 - m_Z^2)^2 (m_{N_i}^2 + 2m_Z^2)}{m_{N_i}^3 v^2}$$

$$v = 246 \text{ GeV. Total decay width: } \Gamma_{N_i} = \sum_{\alpha=e,\mu,\tau} \Gamma(N_i \rightarrow \ell_\alpha W) + \Gamma(N_i \rightarrow \nu_\alpha Z) \text{ ?}$$

$$\blacktriangleright \Gamma_{N_i} \propto \sum_{\alpha=e,\mu,\tau} |R_{\alpha i}|^2 = (R^\dagger R)_{ii}, \quad c\tau \propto 1/\Gamma_{N_i}$$

$$\blacktriangleright \text{Casas-Ibarra: } R = m_D m_N^{-1} = U^* \sqrt{D_\nu} \mathcal{O} \sqrt{m_N^{-1}}$$

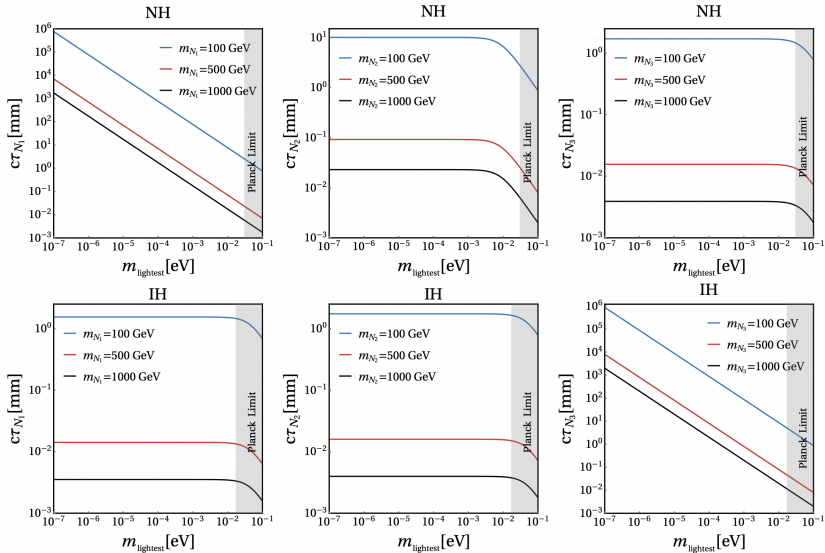
$$R^\dagger R = \sqrt{m_N^{-1}} \mathcal{O}^\dagger D_\nu \mathcal{O} \sqrt{m_N^{-1}}$$

$$\blacktriangleright \mathcal{O} = \mathbb{I}: R^\dagger R = \sqrt{m_N^{-1}} D_\nu \sqrt{m_N^{-1}} = \text{diag}\left(\frac{m_1}{m_{N1}}, \frac{m_2}{m_{N2}}, \frac{m_3}{m_{N3}}\right)$$

Normal hierarchy (NH): $m_1 < m_2 < m_3$
 Inverted hierarchy (IH): $m_3 < m_1 < m_2$

**The lightest neutrino mass
 becomes an independent variable**

If m_{lightest} is sufficiently small, one of the heavy neutrinos can be long-lived



N. Okada, P. Sanyal and R. K. Verma, [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)

How small the VEV, v_2 , of the neutrinophilic Higgs doublet?

How large is the EW pair production of $H^\pm$ at the LHC?

- ▶ Strongest bound on v_2 : $\mu \rightarrow e\gamma$ LFV process.

- ▶ For $\mathcal{O} = \mathbb{I}$, the $H^\pm$ - N loop contribution is dominant:

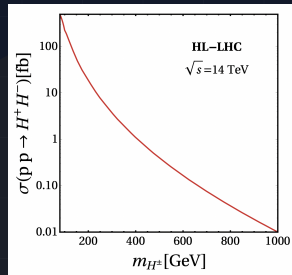
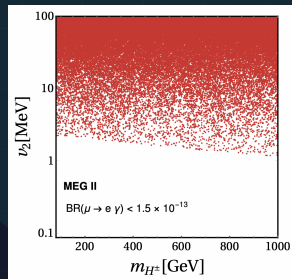
$$\text{BR}(\mu \rightarrow e\gamma) \simeq \frac{3\alpha_e}{16\pi G_F^2 m_{H^\pm}^4 v_2^4} \left| \sum_i^3 m_{D1i}^* m_{D2i} F\left(\frac{m_{N_i}^2}{m_{H^\pm}^2}\right) \right|^2$$

$$F(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1 - x)^4}$$

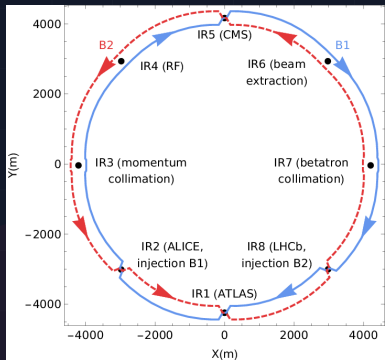
- ▶ **Scan:** $10^{-7} \leq m_{\text{lightest}} \leq 10^{-1}$ eV, $80 \leq m_{H^\pm} \leq 1000$ GeV, $m_{N_1} < m_{H^\pm}$ in NH and $m_{N_3} < m_{H^\pm}$ in IH. $v_2 \lesssim \mathcal{O}(1)$ MeV is excluded. $v_2 = 10$ MeV is considered throughout.

- ▶ At the LHC, $H^\pm$ pair production is γ/Z mediated EW process. For $m_{H^\pm} \gtrsim 400$ GeV, the cross section falls below 1 fb.

N. Okada, P. Sanyal and R. K. Verma, [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)



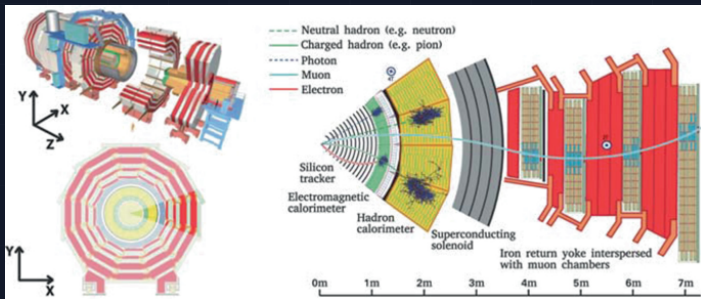
LHC: Large Hadron Collider



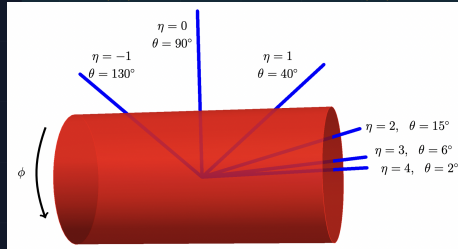
- ▶ Largest particle accelerator of 27 Km circumference.
- ▶ **Main Detectors:** CMS, ATLAS, LHCb and ALICE.
- ▶ **Major Success:** Discovery of Higgs boson and hadronic states, first creation of quark gluon plasma and observation of rare decays $B_s^0 \rightarrow \mu^+ \mu^-$.

Runs	Years	E_{beam} [TeV]	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]
Run 1	2010 – 2011	3.5	7.0	~ 5
Run 1	2012	4.0	8.0	~ 20
Run 2	2015 – 2018	6.5	13.0	~ 140
Run 3	2022 – 2026	6.8	13.6	~ 330
HL-LHC	2030 – 2041	7.0	14.0	3000 (target)

CMS detector and Physics Objects

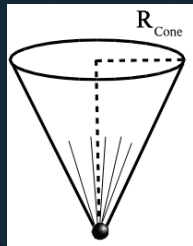
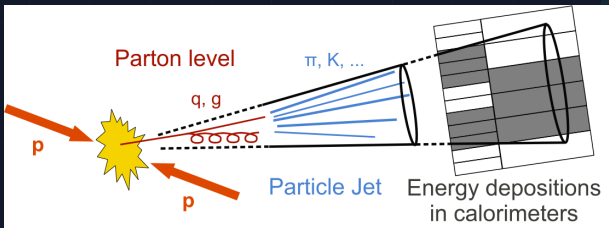


Barrel: $|\eta| \lesssim 1.5$, **Endcaps:** $1.5 \lesssim |\eta| \lesssim 2.5$



- **Physics Objects:** electrons (e), muons (μ), photons (γ), jets (j) and MET p_T^{miss} are reconstructed based on particle-flow (PF) algorithm.

- **Kinematics:** $p_T = \sqrt{p_x^2 + p_y^2}$, $\phi = \tan^{-1} \frac{p_y}{p_x}$, $\eta = \ln \cot \frac{\theta}{2}$, $p_T^{miss} = \left| - \sum_{obs} \vec{p}_T \right|$
 $m_{inv}^2 = \left(\sum_j p_j \right)^2$, $\Delta R_{ij} = \sqrt{\Delta \eta_{ij}^2 + \Delta \phi_{ij}^2}$, $\underbrace{|d0|}_{\text{used for LLP searches}}$ (transverse impact parameter)



- ▶ A **Jet** is a collimated spray of hadrons (charged/neutral) that move towards the same direction in the detector.
- ▶ Suitable jet clustering should be implemented – (1) cone algorithms (2) sequential clustering algorithms.
- ▶ **Light Jets:** jets initiated by light quarks (u, d, s) or by gluons. **Heavy-flavor jets:** jets initiated by c quarks (c -jets) or b quarks (b -jets).

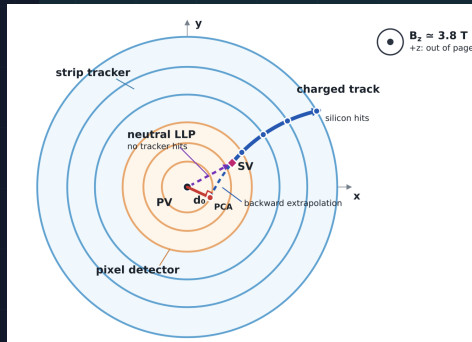
Neutral LLP searches in CMS

- Neutral Long-Lived Particles: N_1 in NH and N_3 in IH.

[A] Decay Length: $\underbrace{\beta\gamma}_{\text{Lorentz boost}} \times \underbrace{c\tau}_{\text{proper decay length}}$

- [B] LLPs follow an exponential probability distribution of decay.

- The transverse impact parameter, $|d_0|$, is defined as the distance between the point of closest approach of the charged track and the primary vertex in the transverse plane.
- Notable mention: **FASER** and its **HL-LHC** upgrade for LLP searches.



Phenomenological Simulation

FeynRules translates a theoretical Lagrangian (SM/BSM) into machine-readable Feynman rules. The output is interfaced with **MadGraph**

MadGraph calculates the matrix elements and generate hard scattering events at the parton level. The output events are interfaced with **Pythia**

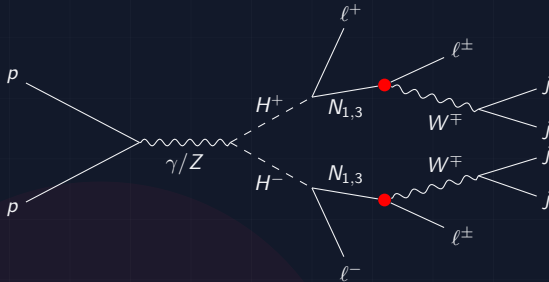
Delphes simulates the detector effects by implementing smearing to momenta and energies of physics objects along with detector efficiencies $\epsilon(p_T, \eta, \dots)$

CERN ROOT for analysing the final simulated scattering events

Pythia performs parton showering and hadronization and **FastJet** implements jet clustering algorithms to reconstruct jets. The output is forwarded to **Delphes**

HL-LHC: $\sqrt{s} = 14 \text{ TeV}$, 3000 fb^{-1} luminosity

► N_1 (NH) and N_3 (IH) are long-lived.



Displacement of leptons is measured by the transverse impact parameter $|d_0|$

CMS provides $|d_0|$ dependent reconstruction efficiencies of e, μ for $|d_0| < 20 \text{ mm}$

For $|d_0| > 20 \text{ mm}$, a linear extrapolation, vanishing at 100 mm is adopted in MadAnalysis

Final state: $4\ell 4j$, can provide a hint of Majorana neutrinos by lepton number violation by two units

Leptons (e, μ): $p_T > 10$ GeV, $|\eta| < 2.5$

Jets: $p_T > 25$ GeV, $|\eta| < 2.5$

Prompt lepton: $|d_0| < 0.1$ mm, $|d_z| < 1$ mm

Displaced lepton: $|d_0| > 2$ mm, $|d_z| < 100$ mm

Impose $|d_0|$ -dependent lepton efficiency weight

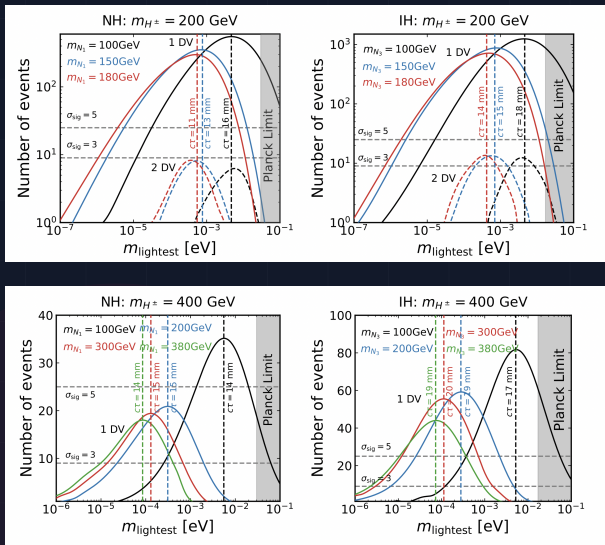
1DV selection

- (1) Require at least 2 jets and at least 2 leptons
- (2) Require ≥ 1 prompt lepton and ≥ 1 displaced lepton
- (3) Reconstruct $W \rightarrow jj$ with $|m_{jj} - m_W| < 25$ GeV
- (4) Require $\Delta R(\ell^{\text{disp}}, jj) < 2$
- (5) If largest $|d_0|$ lepton fails, test the second-largest $|d_0|$ lepton, and so on
- (6) Successful: Accepted as 1DV event

2DV selection

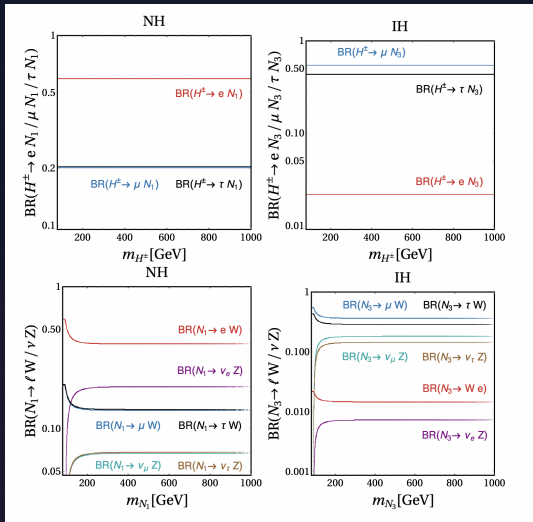
- (1) Require at least 4 jets and at least 3 leptons
- (2) Require ≥ 1 prompt lepton and 2 displaced leptons
- (3) Use the 4 leading jets and form 2 dijet candidates
- (4) Require $|m_{jj_1} - m_W| < 25$ GeV and $|m_{jj_2} - m_W| < 25$ GeV
- (5) Require $\Delta R(\ell_{1,2}^{\text{disp}}, jj_1) < 2$ and $\Delta R(\ell_{2,1}^{\text{disp}}, jj_2) < 2$
- (6) Successful: Accepted as 2DV event

N. Okada, P. Sanyal and R. K. Verma, [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)

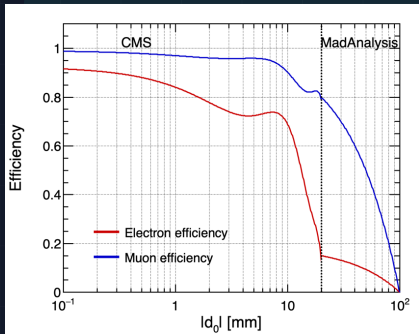


N. Okada, P. Sanyal and R. K. Verma, [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)

- ▶ HL-LHC: $\sqrt{s} = 14$ TeV and 3000 fb^{-1} luminosity.
- ▶ $\sigma(pp \rightarrow H^+ H^-) \simeq 20$ (1) fb for $m_{H^\pm} = 200$ (400) GeV.
- ▶ Signal yield peaks at $c\tau \simeq 10\text{--}20$ mm, as many events pass $|d_0| > 2$ mm while staying inside the tracker.
- ▶ **The 1DV selection yields larger signal events than the 2DV selection.**
- ▶ **Signal events in IH is higher than the signal events in NH.**



N. Okada, P. Sanyal and R. K. Verma, [arXiv:2604.00866](https://arxiv.org/abs/2604.00866)



Prepared for the talk

- ▶ NH favors the electron mode, while IH favors the muon mode.
- ▶ Muons have higher $|d_0|$ efficiency than electrons.

Why "?" in slide 7

- ▶ $H_1 - H_2$ mixing is proportional to $\frac{v_2}{v}$, which leads to a small Yukawa coupling of N_R with SM Higgs h :

$$-\mathcal{L}_y^h = \frac{1}{\sqrt{2}} \sum_{\alpha i} y_D^{\alpha i} \frac{v_2}{v} \bar{\nu}_{L\alpha} N_{Ri} h + h.c.$$

$$\Gamma(N_i \rightarrow \nu_\alpha h) = \frac{|R_{\alpha i}|^2}{16\pi v^2} \frac{(m_{N_i}^2 - m_h^2)^2}{m_{N_i}}$$

- ▶ Total decay width: $\Gamma_{N_i} = \sum_{\alpha=e,\mu,\tau} \Gamma(N_i \rightarrow \ell_\alpha W) + \Gamma(N_i \rightarrow \nu_\alpha Z) + \underbrace{\Gamma(N_i \rightarrow \nu_\alpha h)}_{\text{additional term}}.$
- ▶ Consequently, $\sigma_{\text{prod}} = \sigma(pp \rightarrow H^+ H^-) \times BR(H^\pm \rightarrow \ell^\pm N)^2$ will be slightly reduced.

Conclusion

BSM Higgs doublet can couple exclusively to the right-handed neutrinos and SM leptons. The small VEV of the extra Higgs doublet can generate small Dirac neutrino masses without requiring extremely small Yukawa couplings

The $H^\pm$ from the neutrinophilic Higgs doublet can be produced via EW process, and can decay dominantly into heavy neutrinos and charged leptons

This provides a mixing unsuppressed production mechanism for SM gauge singlet long-lived heavy neutrinos.

The long-lived heavy neutrinos can give rise to displaced vertex signatures at the LHC

Within the canonical seesaw, one of the heavy neutrinos can be long-lived while remaining consistent with neutrino oscillation data, and its lifetime is inversely proportional to the lightest neutrino mass

Backup

